# UNITED STATES PATENT APPLICATION

## FOR

## IMPROVED TRANSMISSION OF FREE-SPACE COMMUNICATION SIGNALS THROUGH WINDOWS

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# IMPROVED TRANSMISSION OF FREE-SPACE OPTICAL COMMUNICATION SIGNALS THROUGH WINDOWS

## BACKGROUND OF THE INVENTION

5        ### Field of the Invention

The present invention generally relates to free-space optical

communications systems, and, more specifically, to a method and

apparatus for improving transmission of free-space optical communication

signals through windows with surface imperfections, such as pitting,

10      surface waviness, and other non-flat surface distortions.

### Background Information

With the increasing popularity of wide area networks (WANs), such

as the Internet and/or the World Wide Web, network growth and traffic

has exploded in recent years. Network users continue to demand faster

15      networks and more access for both businesses and consumers. As

network demands continue to increase, existing network infrastructures

and technologies are reaching their limits.

An alternative to present day hardwired or fiber network solutions is

the use of wireless optical communications. Wireless optical

20      communications utilize point-to-point communications through free-space

and therefore do not require the routing of cables or fibers between

locations. Thus, wireless optical communications are also known as free-

space or atmospheric optical communications. For instance, in a free-

space optical communication system, a beam of light is directed through

free-space from a transmitter at a first location to a receiver at a second location. Data or information is encoded into the beam of light, and therefore, the information is transmitted through free-space from the first location to the second location.

5       A conventional free-space optical system is shown in FIGURES 1A and 1B. The free-space optical system includes a pair of transceiver stations 10 that are typically located on or in separate buildings or towers, such as depicted by buildings 11 and 12. Each transceiver station 10 includes a primary collector 13 to which a secondary mirror 14 is coupled

10      via a plurality of rigid struts 16. The transceiver stations further include a transmitted signal lens 18 mounted within secondary mirror 14, and a set of transmitter/receiver optics and electronics 20. All of components 13, 14, 16, 18, and 20 are operatively coupled to a yoke that is connected to a base 22 via a gimble assembly, such that these components are all

15      moved in response to a gimbled movement of the yoke relative to a static surface on which the base 22 is placed.

      With reference to FIGURE 1B, data is transmitted from a transceiver station 10T to a transceiver station 10R in the following manner. An optical signal 24 is generated by transmitter/receiver optics

20      and electronics 20T of transceiver station 10T and directed through an opening 26T defined in primary collector 13T towards transmitted signal lens 18T, which produces a collimated signal 28. As collimated signal 28 moves toward transceiver station 10R, the width of the signal diverges

very gradually.  As will be recognized by those skilled in the art, the

divergence of the various optical signals depicted in the Figures contained

herein are exaggerated for clarity.  Upon reaching transceiver station 10R,

the outer portions of collimated signal 28 impinge upon primary

5    collector 13R, which comprises a concave mirrored surface that redirects

those portions of the signal that impinge upon it toward secondary

mirror 14R.  Collimated signal 228 is then reflected by

secondary mirror 14R towards the secondary mirror's focal point 30,

where it is received by transmitter/receiver optics and electronics 20R.

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## SUMMARY OF THE INVENTION

The present invention provides a method and apparatus for improving the transmission of free-space optical communications signals through windows having surface imperfections, such as pitting, waviness, and other non-flat surface distortions. A void-filling material is applied to one or both surfaces of the window to fill any non-flat surface voids on those surfaces in areas through which the optical communications signal passes. In one embodiment, the window has one surface (typically the exterior) that is imperfect and a substantially perfect (i.e., with no or very minor surface imperfections) optically translucent plate is mounted to this imperfect window surface so as to capture the void-filling material between an inside surface of the optically translucent plate and the imperfect surface of the window. In another embodiment, both surfaces of the window are imperfect. As before, the void-filling material is applied to the second imperfect surface of the window to fill any surface voids an the area through which the optical signal passes, and a second substantially perfect optically translucent plate is mounted to this second imperfect surface to capture the void-filling material. The void-filling material is selected to have an index of refraction that substantially matches an index of refraction for the window at an optical wavelength corresponding to the free-space optical communication signal. As a result, the adverse effects that would normally be caused to free-space

optical communication signals that are passed through imperfect windows with surface distortions are substantially eliminated.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and many of the attendant advantages of this invention will become more readily appreciated as the same becomes better understood by reference to the following detailed description, when

5 taken in conjunction with the accompanying drawings, wherein:

FIGURE 1A is an illustration of a conventional free-space optical communications system that uses on-axis primary and secondary reflectors and provides transmitting and receiving capabilities at a pair of transceiver stations disposed at remote locations within respective

10 buildings;

FIGURE 1B shows how an optical communications signal is transmitted by a first transceiver station and received by a second transceiver station;

FIGURE 2 is a schematic diagram comprising a cross-section of an

15 imperfect window that is used to illustrate the adverse effects caused to optical communication signals as they pass through windows with imperfect surfaces;

FIGURES 3A and 3B are schematic diagrams illustrating how light beams are bent when the pass through materials with different indexes of

20 refraction in accordance with Snell's law;

FIGURES 4A and 4B are schematic diagrams illustrating an adverse effect caused to parallel light beams when one of the beams passes through a surface distortion in a window;

FIGURE 5A is a cross-section schematic diagram illustrating a first

embodiment of the invention in which a void-filling material such as a

liquid or gel is applied to an imperfect window surface to fill any surface

voids in an area of the imperfect surface through which an optical

5    communications signal passes, wherein the void-filling material is

captured by a substantially perfect optically translucent plate that is

mounted to the window;

FIGURE 5B illustrates an alternate embodiment of FIGURE 5A in

which a protective coating is applied to the exterior surface of the optically

10    translucent plate to protect the plate from environmental damage;

FIGURE 6 is an elevational view corresponding to the

embodiments illustrated in FIGURES 5A and 5B;

FIGURE 7 is a cross-section schematic diagram illustrating an

embodiment of the invention in which a planar cavity is defined in the

15    substantially perfect optically translucent plate and the void-filling material

is inserted into a cavity defined between the optically translucent plate and

the window;

FIGURE 8 is a cross-section schematic diagram illustrating an

embodiment of the invention in which a void-filling material is applied over

20    the surface of an imperfect window in a non-solid form and cured into a

solid form such that the outside surface of the void-filling material is

substantially perfectly planar;

FIGURE 9 is a cross-section schematic diagram illustrating an

embodiment of the invention in which a void-filling material is applied over the surface of an imperfect window and covered with a flexible optically translucent sheet of material;

FIGURE 10 is a schematic diagram corresponding to the

5 embodiment of FIGURE 5A illustrating the effect of filling a surface void with a void-filling material having an index of refraction that substantially matches the index of refraction of the window material;

FIGURE 11 is a schematic diagram illustrating how transmission of a free space optical communications signal that is substantially normal to

10 an imperfect window is improved by an implementation of the invention;

FIGURE 12 is a schematic diagram illustrating how transmission of a free-space optical communications signal that passes through an imperfect window at a significant angle of incidence is improved by an implementation of the invention

15 FIGURE 13 is a schematic diagram corresponding to an embodiment of the invention in which the void-filling material and substantially perfect optically translucent plates are applied to both surfaces of a window; and

FIGURE 14 is a schematic diagram corresponding to the

20 embodiment of FIGURE 8 illustrating the effect of applying a void-filling material having an index of refraction that substantially matches the index of refraction of the window material over the surface of an imperfect window;

FIGURE 15 is a schematic diagram illustrating the effect caused to a pair of parallel beams when one of the beams passes through a surface imperfection that is filled with a void-filling material that has an index of refraction that does not match the index of refraction of the window.

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## DETAILED DESCRIPTION

In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one having ordinary skill in the art that the
5    specific detail need not be employed to practice the present invention. In other instances, well-known materials or methods have not been described in detail in order to avoid obscuring the present invention.

In one example embodiment of the present invention, point-to-point free-space optical communications are provided from a transmitter to a
10   receiver. The transmitter and receiver may be located at the same location or at different locations such as on different buildings within a line of sight of each other. It is appreciated that the transmitter and the receiver may be parts of transceivers, or transmitter-receiver combinations, at their respective locations, such that bi-directional
15   communications are provided. In the example embodiment, the transmitter includes an optical source that generates an optical communications beam, such as a laser beam or the like, on which data or information is modulated. The optical communications beam is not limited to being monochromatic or to any particular wavelength or color and may
20   include the visible light as well as ultra violet or infra-red portions of the spectrum.

With reference to the conventional free-space communication system shown in FIGURES 1A and 1B, in many system implementations,

optical signals will need to pass through building windows, such as

building windows 34 and 36, which respectively correspond to exterior

office or room windows in buildings 11 and 12. As shown in FIGURE 2,

this may presents a problem when the surfaces on one or both sides of

5      the window are imperfect. As used herein, an imperfect window

comprises a sheet of material, such as glass, having at least one primary

surface with surface imperfections, such as pits, roughness, waviness,

and other non-flat surface distortions, which cause localized surface areas

on the window to not be co-planar with a plane defined to be coincident

10     with the imperfect surface of the window. For example, the outside of

building windows are exposed to environmental conditions that may

roughen the exterior surface of the windows, as depicted by surface

imperfections 38 on window 36. In other instances, windows are

manufactured with similar imperfections. These non-flat localized surface

15     areas may displace and even break-up the transmitted or received

beams, seriously impairing link margin. The effect of surface

imperfections 38 on collimated beam 28 is illustrated in FIGURE 2,

wherein portions of the collimated beam, depicted by light rays 40, are

caused to be redirected at various angles when they pass through an

20     imperfect window 37, as depicted by light rays 40'. Details concerning

what causes these adverse effects are discussed below.

For each ray 40-40', the degree of redirection will generally be a

function of the incidence angle of the ray relative to the normal of the

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localized portions of the glass surfaces it passes through, and the index of refraction of the window material. The index of refraction of a material, n, is defined as the ratio of the velocity of light in a vacuum (c = 2.998 x $10^8$m/sec) to the velocity that light passes through the material, v, i.e.,

5
$$n = c/v \qquad (1)$$

The index of refraction of a material is generally dependent on its density and the wavelength of the light under consideration. For most calculations, the index of refraction of air is considered to be 1.0. If a higher degree of accuracy is required, for yellow light (wavelength = 580

10    nanometers) air has an index of refraction of 1.0002 or 1.0003 (depending on the measurement source) under standard atmospheric pressure and temperature (29.92 inches Hg, 70°F).

In most instances, the material for a building window will comprise some type of glass. Depending on the particular glass used in the

15    window, the index of refraction for a window will generally range from 1.4 – 1.9, with a nominal value of 1.5. For example, for yellow light, crown glass has an index of refraction of 1.517, moderately dense flint glass has an index of refraction of 1.655, and heavy flint glass has a density of 1.89.

Light is considered to travel in light waves. Because light waves

20    travel at different speeds in different mediums, when light passes from a lower index to a higher index material (e.g., an air/window boundary), the wave front must slow down, causing the light beam to bend. Conversely, when light exits the higher index material, the wave front speeds up to its

original speed.

The degree of bending is a function of the angle of the incident ray with respect to the surface normal of the material being entered, and the index of refraction of the two materials. When light is incident on an

5    interface between two materials, it can be reflected or refracted. Both situations are described quantitatively by Snell's Law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad (2)$$

wherein $n_1$ is the index of the first (incident) material, $n_2$ is the index of the second medium, $\theta_1$ is the angle of the incident ray (also known as

10    the angle of incidence) with respect to the surface normal at the interface between the two materials, and $\theta_2$ is the angle of the outgoing ray with respect to the surface normal.

Applying Snell's law, the bending caused to an exemplary light ray 42 as it passes through a perfect glass plate 39 (i.e. a plate with no

15    surface imperfections) at an incident angle $\theta_1$ is shown in FIGURE 3A. In this example, the light passes through air having an index of refraction $n_1$ = 1.0 and glass having an index of refraction $n_2$ = 1.5. It is noted that if the two face surfaces of the glass plate are parallel, the incident angle of the light ray entering the glass plate and the angle of a corresponding

20    outgoing ray 42' exiting the glass plate will be equal (both depicted as $\theta_1$ in FIGURE 3A).

When a received or transmitted optical beam passes through a

perfect window, all of the beam's light rays 44 are redirected the same

degree, with the result that incoming parallel light rays exit as parallel

rays 44', even if the incidence angle is significant, as shown in

FIGURE 3B. In contrast, when one of parallel light rays 46 and 48 pass

5    through a surface imperfection in a imperfect glass plate 50, as

exemplified by a pit 52, and the other ray passes through another perfect

portion of the glass plate, the light rays exit the glass plate at non-parallel

angles, as depicted by exiting light rays 46' and 48' in FIGURE 4A.

As depicted in FIGURES 4A and 4B, the path of light ray 46 is the

10   same as light ray 42 in FIGURE 3, illustrating an ideal condition in which

the surface of imperfect glass plate 50 is perfectly flat in the areas

corresponding to where light ray 46 enters the glass plate and where light

ray 46' exits the glass plate. Applying Snell's law, the path of light ray 48

is as follows. The light ray enters the glass at an angle of incidence $\theta_3$

15   relative to the normal 54 of a surface 56, whereupon it is bent at an angle

$\theta_4$ relative to normal 54. Upon exiting the glass, the light ray has an angle

of incidence $\theta_5$ relative to a normal 58, and exits the glass at an angle of

$\theta_6$.

There are three effects caused by surface imperfections, such as

20   pit 52. First, the distance between parallel light rays is changed, as

depicted in FIGURE 4B wherein the distance $D_1$ between incoming light

rays 46 and 48 is substantially smaller than the distance $D_2$ between

exiting light rays 46' and 48', wherein $D_1$ and $D_2$ are measured at the input side and exit side of imperfect glass plate 50. Second, light rays 46' and 48' are no longer parallel, and now are diverging at an angle $\theta_7$.

A third effect caused by surface imperfections is that the phase

5   between light rays may be changed. Generally, free-space optical communication signals comprise high-energy light beams, such as those generated by lasers, which are modulated at a very high frequency. By varying the "on" (or alternatively "off") time period, the modulated light beam can be made to produce a digital communication signal. As light

10  passes through the glass, its speed is reduced. If the travel path through the glass is longer for some light rays than others, there will be a difference in the phase of those light rays. This difference can cause parts of the beam to interfere with each other, resulting in a beam containing sections with no light power at all.

15  The present invention addresses the foregoing problems caused by window surface imperfections by creating planar incident surfaces that appear (from the light rays' standpoint) to be substantially identical to that of encountered when passing through perfect glass, or other material used for building windows. With reference to FIGURES 5A and 6, in one

20  embodiment, a void-filling material 58 comprising gel or liquid having an index of refraction that substantially matches the window material is applied to the window (e.g., window 37), whereupon a substantially perfect plate of glass, plastic, or other optically translucent (i.e., light at the

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working wavelength passes through the material with no or minimal

distortion) material 60 is applied over the index-matching void-filling

material to capture the gel or liquid, thereby filling any surface voids 52

with the gel or liquid and forming a substantially planar incidence surface

5    between the substantially perfect optically translucent plate 60 and the

void-filling material.  In one embodiment, substantially perfect optically

translucent plate 60 is secured to imperfect window 37 by means of an

adhesive 62.  As shown in FIGURE 6, void-filling material 58 is applied to

the center portion of substantially perfect optically translucent plate 60 that

10    includes an area 64 through which collimated beam 28 passes, while

adhesive 62 is applied around the periphery of the plate.  Various types of

adhesives may be used, including instant fixture adhesives such as

cynoacrylates (a.k.a., "super glues") and contact cements, various types

of epoxies designed for glass-type surfaces, and ultraviolet-cured

15    adhesives, such as those manufactured by the Loctite corporation.  An

optional means for securing substantially perfect optically translucent

plate 60 to imperfect window 37 is to secure the optically translucent plate

to the window frame in which the imperfect window is held (not shown).

Substantially perfect optically translucent plate 60 is defined to be

20    "substantially perfect" and "translucent" in the following manners.  It is

termed "substantially perfect" because the primary faces of the plate are

substantially flat throughout with no or very minor surface imperfections.

The term "translucent" means that the material enables optical

communication signals to pass through it with minimal energy loss,

including light signals having wavelengths in the non-visible spectrum.

Suitable materials include various types of glasses, preferably having a

ground exterior face or a face having a similar finish. Optionally, various

5    types of high-performance translucent plastics may be used, such as

Plexiglas™ and other carbonate plastics. In some embodiments, such as

shown in FIGURE 5B, it may be desired to apply a sealing/protective

coating or layer 66 to the exterior surface of the substantially perfect

optically translucent plate, which serves the functions of ensuring the

10   flatness of the exterior surface and/or protecting the exterior surface

against environmental damage over the life of the installation. Although

illustrated as being rectangular in FIGURE 6, substantially perfect optically

translucent plate 60 may be of any configuration, including circular. For

example, a ground optical flat having a circular shape may be used.

15        There are various techniques for encapsulating void-filling

material 58 between the imperfect window face and the inside surface of

substantially perfect optically translucent plate 60. In one embodiment,

the substantially perfect optically translucent plate is laid flat and an

adhesive is applied to the periphery of the top surface of the plate,

20   whereupon a void-filling material 58 comprising a gel is applied to the

plate within the area outlined by the adhesive. The plate is then quickly

flipped upright and held against the window (e.g., imperfect window 37)

until the adhesive cures to the point that it can hold the plate in place. In

another embodiment, a substantially perfect optically translucent plate 60

is held against or affixed at one or more areas to imperfect window 37,

whereupon a void-filling material 58 is applied around periphery areas of

the plate. The voids in the area of imperfect window 37 inside of its

5    peripheral areas are then filled with void-filling material 58 via a capillary

or wicking action of void-filling material, which moves a portion of the void-

filling material from the periphery areas to the inside areas.

An alternate assembly method is illustrated in FIGURE 7, wherein a

substantially perfect optically translucent plate 60' having a planar

10   cavity 68 defined in its inside surface is used. In one embodiment,

adhesive 62 is applied to the periphery of the plate, and the plate is held

against imperfect window 37 until the adhesive is adequately cured. At

this point, void-filling material 58 may be added by inserting the material

into the void between the plate and the window, which includes cavity 68

15   and a portion of the imperfect window opposite the cavity. For example,

the void-filling material may be inserted with through a hole in the plate

with a syringe 70, whereupon the hole is plugged to prevent the void-filling

material from escaping the cavity. This embodiment is particularly well-

suited when low viscosity liquids are used for void-filling material 58.

20   Another embodiment of the invention is illustrated in FIGURE 8. In

this embodiment, a void-filling material 58' is applied over one or both

surfaces of imperfect window 37 as a gel or liquid, and cures into a solid.

For example, void-filling material 58' may be sprayed if it initially

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comprises a liquid or applied with a brush or roller if is initially comprises a

gel. The void-filling material used for this embodiment will need to cure in

a manner that creates a substantially perfectly planar exterior surface, and

should be applied over an area that encompasses the area of the window

5    through which the optical signals pass.

Yet another embodiment of the invention is illustrated in FIGURE 9.

In this embodiment, a void-filling material 58 is applied over one or both

surfaces of imperfect window 37 as a gel or liquid, and a flexible optically

translucent (to the optical signal wavelength) sheet of material 71 is

10    applied over the void-filling material so that the voids in imperfect

window 37 are filled with the void-filling material.

An exemplary result obtained by the embodiment of FIGURE 5A is

illustrated in FIGURE 10. In the Figure, a light ray 72 passes through

perfect optically translucent plate 60 and imperfect window 37, while a

15    parallel light ray 74 passes through perfect optically translucent plate 60,

void-filling material 58, and imperfect window 37. Because the index of

refraction for the window glass and the void-filling material are the same

(in this example, n = 1.5 for both), light rays 72 and 74 are caused to

follow parallel paths. As a result, the distance between the rays before

20    entering and after exiting the window, as depicted by distances $D_1$ and $D_2$,

remains the same. In addition, the phase of the light rays remain

synchronized. Thus, by applying the principles of the invention to optical

communication systems that transmit and receive signals through

imperfect windows, the problems previously caused by the imperfect surface of the windows may be corrected, as illustrated in FIGURES 11 and 12.

It is noted that in the forgoing example, the index of refraction of the perfect optically translucent plate ($n_4$ = 1.8) is not the same as the glass and the void-filling material ($n_2$ = $n_3$ = 1.5). This type of configuration may be used in most circumstances, although it is preferable that when such configurations are used, both sides of the perfect optically translucent plate are substantially planar and devoid of imperfections. One reason for using a material with a higher index of refraction for substantially perfect optically translucent plate 60 than that used for the window is that such materials may exhibit better resistance to environmental damage.

In addition to applying the method and apparatus of the invention to a single side of an imperfect window, the same may also be applied to both sides of the window if imperfections exist on both of those sides. Exemplary results obtains by this embodiment are illustrated in FIGURE 13.

An exemplary result obtained by the embodiment of FIGURE 5A is illustrated in FIGURE 14. In the Figure, a light ray 82 passes through a thin layer of void-filling material 58' and imperfect window 37, while a parallel light ray 84 passes through an a portion of void-filling material 58' in which a void 52 exists, and then passes through imperfect window 37.

Because the index of refraction for the window glass and the void-filling

material are the same (in this example, n = 1.5 for both), light rays 82 and

84 are caused to follow parallel paths, which are depicted as paths 82'

and 84'. As a result, the distance between the rays before entering and

5    after exiting the window, as depicted by distances $D_1$ and $D_2$, remains the

same. In addition, the phase of the light rays remain synchronized.

There are two additional considerations that may affect the

performance of systems that implement the invention. Both

considerations concern the difference between the indexes of refraction of

10   the imperfect window and the void-filling material. As illustrated in

FIGURE 15, if the index of refraction of void-filling material 58 does not

substantially match the index of refraction of the window, problems may

result, such as the change in the displacement of parallel light rays 92 and

94 depicted in the Figure. The other consideration is that the matching

15   indexes of refraction need to apply to the wavelength of the light used in

the free-space optical communication signal.

It is important to recognize that the index of refraction for a material

isn't constant for all wavelengths of light, but actually may vary

considerable. This change in index of refraction vs. light wavelength is

20   what enables a prism to separate white light (i.e., a mix of all visible

wavelengths of light) into a visible color spectrum. In one embodiment,

free-space optical communication signals used in conventional free-space

optical communication system 10 include signals having wavelengths of

1550 nanometers and 1625 nanometers, both of which are in the infrared spectrum. Accordingly, perfect optically translucent plate 60 needs to be substantially optically translucent to infrared light having a wavelength corresponding to the free-space optical communications signal that is used. In general, the optical signals used by the invention may fall within the infrared spectrum of 700 – 1700 nanometers. It is noted that other wavelengths may be used as well, including visible wavelengths and ultra-violet wavelengths, such that the wavelength of the light signal may generally fall within the range of 450 – 1750 nanometers.

In the foregoing detailed description, the method and apparatus of the present invention have been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the present invention. The present specification and Figures are accordingly to be regarded as illustrative rather than restrictive. Furthermore, it is not intended that the scope of the invention in any way be limited by the above description, but instead be determined entirely by reference to the claims that follow.